NEW GAINP/GAAS-HBT LARGE-SIGNAL MODEL FOR POWER APPLICATIONS

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ABSTRACT

A new GaInP/GaAs HBT model for power applications is presented. It is based on the GUMMEL-POON model. Additionally, it accounts for the increase of the thermal resistance at high temperatures and the high collector-current base push-out effect. The model is validated for GaInP/GaAs HBTs.

INTRODUCTION

Hetero-bipolar transistors (HBTs) are ideal devices for microwave power applications because of their high linearity and the ability to operate at high current densities, which yields record power levels for a given device size. For transistor optimization and for power amplifier design, a large-signal HBT model is necessary that includes all relevant effects.

For high-power operation, the two main limiting effects are self heating due to the dissipated power and base widening due to high collector currents (KIRK effect, base push-out). This is in contrast to conventional bipolar transistors, where high-level injection into the base (WEBSTER effect) and widening of the base-collector space-charge region into the base (EARLY effect, punch through) dominate. In HBTs, both are prevented by the high base doping.

The models on GaAs-based HBTs published so far focus on small current densities ([1], [3], [4]), where self heating depends linearly on dissipated power and base push-out does not occur.

In these papers, the effect of self heating is accounted for by including a constant thermal resistance. At high currents, however, nonlinearity of the thermal resistance becomes important [5].

This is included in our improved model. Furthermore, the KIRK effect is accounted for, which becomes important at high current densities, in our case above ca. 1.5×10^5 A/cm^2.

MODEL

A. Basic Approach

The model is based on the GUMMEL-POON description. An additional diode with series resistor has been included to model the nonideal base-emitter current due to recombination at the heterojunction [2], that leads to different ideality factors of base and collector current (Figs1. and 3.(A)). The diode parameters are extracted from GUMMEL plots.

The intrinsic depletion capacitances and the external parasitics are determined from small-signal S-parameter measurements at open collector condition and in the off region [10]. The remaining elements are determined from small-signal equivalent-circuit element extraction by a linear least-squares method in a wide range of bias points.

B. Thermal Modeling

The dissipated power leads to self-heating of the HBT. This is accounted for by a thermal equivalent circuit, modeled by a thermal capcitance C_{th} and a thermal resistance R_{th}. From the physical point of view, the thermal resistance of the HBT is temperature dependent, because the thermal resistance of GaAs varies with temperature. Therefore, linearization of the HBT's temperature dependence leads to large errors at bias points with high DC power dissipation [5].

To improve the stability of the model, the temperature dependence of the thermal resistance is transformed into a power dependence at constant ambient temperature. It is described by a quadratic formula that allows direct calculation of the thermal resistance from dissipated power. Thus, the thermal resistance can be calculated directly from DC voltages and currents without an additional iteration cycle.

C. KIRK Effect

At high collector currents, the charge of the electrons partly compensates the ionized donors in the space-charge region of the collector [6]. This results in an effective widening of the neutral base into the collector region. As a consequence, current gain and transit frequency decrease [6,7]. The first effect is due to recombinaton in the effective base region, which decreases the base transport factor. It is not necessarily observed in HBTs with high electron lifetimes in the base (see Fig. 4.(B)). The second effect is caused by increased base transit time.

For Si/SiGe-DHBTs, a model for the KIRK effect is presented in [11]. Due to the different electron velocity in GaAs, a new physics-based model of this phenomenon was developed.

The base widening starts abruptly [6,7,8,9] and behaves approximately inversley proportional to the collector current I_C, for I_C beyond an onset current I_k. The effect on base transit time is given by

$$\tau_B = \frac{W_B^2}{\eta\, D_B}$$

with the effective base width W_B, the electron diffusion constant in the base D_B and a factor η that describes the electron drift in the base. The base transport factor is given by

$$\alpha_t = \frac{1}{\cosh\left(\frac{W_B}{L_B}\right)}$$

with the electron diffusion length L_B.

The dependence of base widening on collector current is described directly as a function of the intrinsic voltages. Thereby, no iterations are necessary to calculate the collector current. Only five parameters are required, in addition to the GUMMEL-POON model. The parameters are base and collector width, the slope of the base widening with increasing I_C, and (η D_B) and L_B.

VERIFICATION

The devices under test are a 2 × 20 μm^2 (HBT A) and a 3 × 15 μm^2 (HBT B) single-emitter GaInP/GaAs HBTs designed as elementary cells for power HBTs for 2 GHz applications. The transit frequency of the first without base push-out is about 27 GHz.

DC simulations and measurements for HBT A are shown in Fig. 3. Fig. 3.(A) shows the GUMMEL plots, in Fig. 3.(B), the I-V characteristics with base current I_b as parameter are plotted. The advantages of the new model in the high-current regime are clearly visible.

Fig. 4.(A) presents measured and modeled S-parameters of HBT A.

Fig. 4.(B) shows transit frequency f_t and current gain α_0 of HBT B as functions of collector current. In contrast to HBT A, a variation of the current gain cannot be observed, while the transit frequency decreases from 35 GHz to 12 GHz. In this case, the base widening affects mainly the base transit time, while the current gain remains virtually unchanged due to high electron lifetime in the base.

Note that all figures include current densities of up to 2×10^5 A/cm^2, which are of particular interest for power applications.

In order to demonstrate the large-signal properties, power measurements of the HBT A at two-tone excitation up to an input power of 5 dBm and at one-tone excitation at an input power of 1 dBm are plotted in Fig. 5. Good agreement between measurementsand simulation is found.

CONCLUSIONS

A new GaAs-HBT large-signal model is presented. It is based on the GUMMEL-POON model and includes nonlinear thermal behaviour and high collector current base push-out. These effects prove to be significant in the high-power regime. The extended description yields improved accuracy at high current densities.

REFERENCES

[1] A. SAMELIS, D. PAVLIDIS, "Modeling HBT self-heating", *Applied Microwave & Wireless*, 1996, pp. 108 – 112.

[2] P. CH. GROSSMAN, J. CHOMA, JR., "Large signal modeling of HBT's including self-heating and transit time effects", *IEEE Trans. Microwave Theory Tech.* vol. 40, No. 3, March 1992, pp. 449 464.

[3] Q. M. ZHANG, H. HU, J. SITCH, R. K. SURRIDGE, J. M. XU, "A new large signal HBT model", *IEEE Trans. Microwave Theory Tech.*, Vol. 44, No. 11, Nov. 1996, pp. 2001 – 2009.

[4] C.-J. WEI, J. C. M. HWANG, W.-J. HO, J. A. HIGGINS, "Large-signal modeling of self-heating, collector transit-time, and RF-breakdown effects in power HBT's", *IEEE Trans. Microwave Theory Tech.*, Vol. 44, No. 12, Dec. 1996, pp. 2641 – 2647.

[5] P. BAUREIS, D. SEITZER, "Parameter extraction for HBT's temperature dependent large signal equivalent circuit model", in: *GaAs IC Symposium Digest*, pp. 263 – 266, 1993.

[6] C. T. KIRK, "A theory of transistor cutoff frequency (f_t) falloff at high current densities", *IRE Trans. Electron Dev.*, Mar. 1962, pp. 164 – 174.

[7] R. J. WHITTIER, D. A. TREMERE, "Current gain and cutoff frequency falloff at high currents", *IEEE Trans. Electron Dev.* vol. ED-16, No. 1, Jan. 1969, pp. 39 57.

[8] H. C. POON, H. K. GUMMEL, D. L. SCHARFETTER, "High injection in epitaxial transistors", *IEEE Trans. Electron Dev.* vol. ED-16, No.5, May 1969, pp. 455 457.

[9] K. MORIZUKA, R. KATHO, K. TSUDA, M. ASAKA, N. IIZUKA, M. OBARA, "Electron space-charge effects on high-frequency performance of AlGaAs/GaAs HBT's under high-current-density operation", *IEEE Electron Dev. Lett.* vol. 9, No. 11, Nov. 1988, pp. 570 572.

[10] Y. GOBERT, P. J. TASKER, K. H. BACHEM, "A physical, yet simple, small-signal equivalent circuit for the heterojunction bipolar transistor", *IEEE Trans. Microwave Theory Tech.*, Vol. 45, No. 1, Jan. 1997, pp. 149 – 153.

[11] C. RHEINFELDER, M. RUDOLPH, F. BEIßWANGER, W. HEINRICH, "Nonlinear modelling of SiGe HBTs up to 50 GHz", in: *IEEE MTT-S Digest*, 1997, pp. 877 – 880.

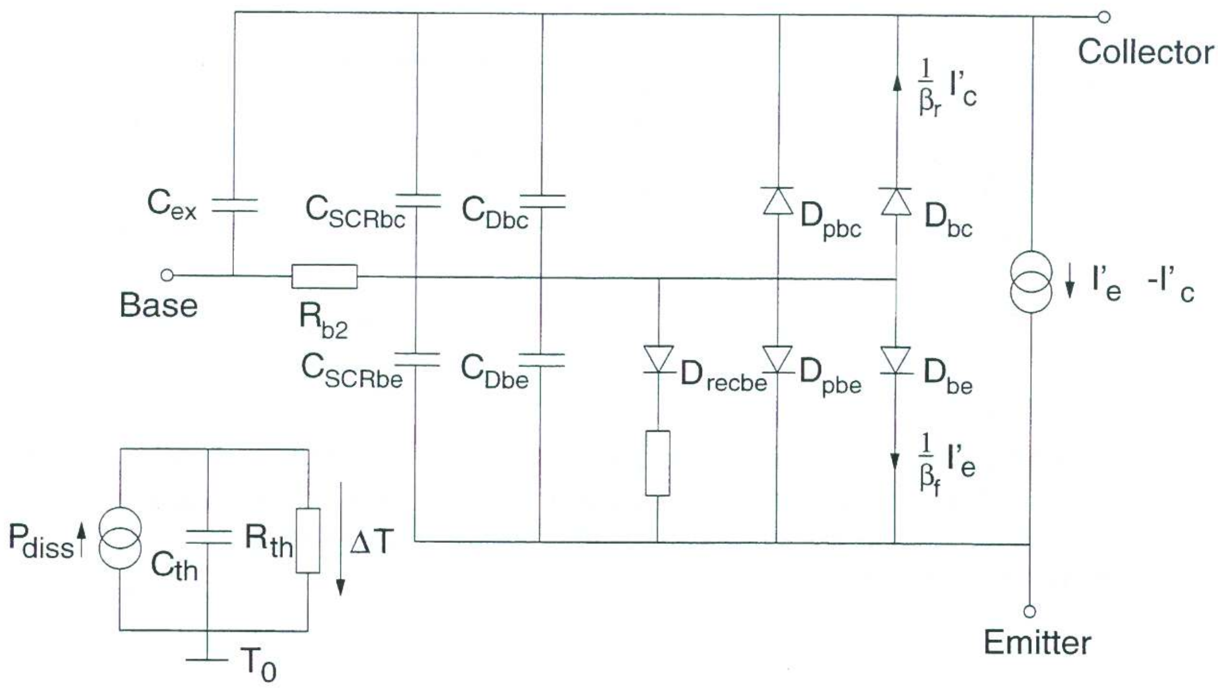


Figure 1.:Intrinsic equivalent circuit of the HBT including thermal equivalent circuit.

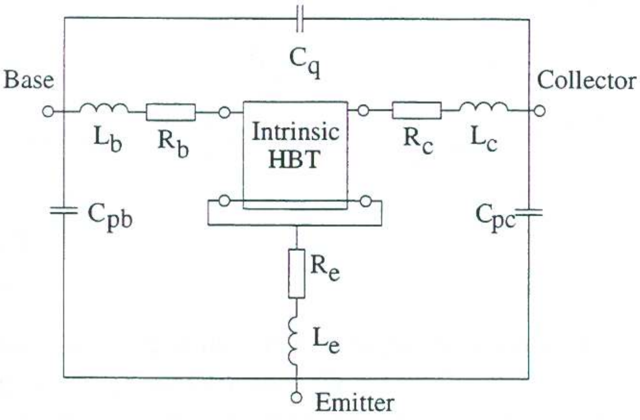
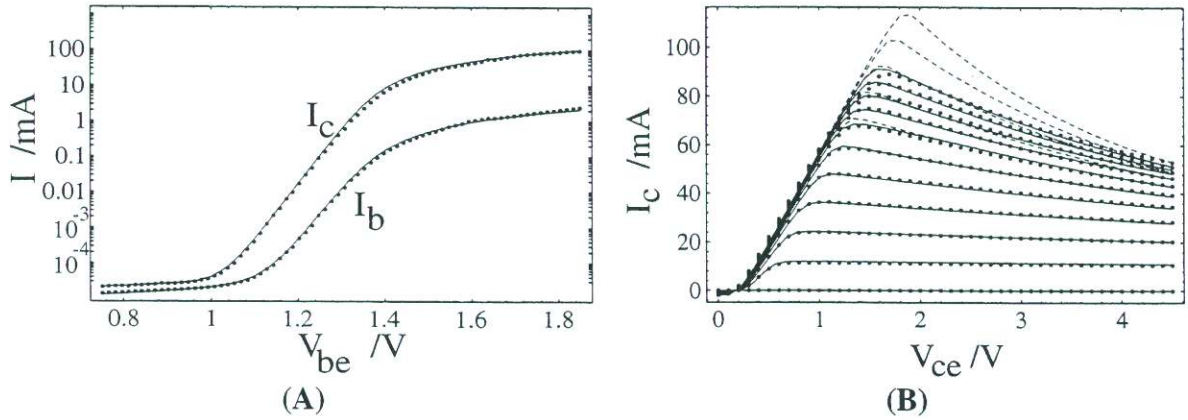
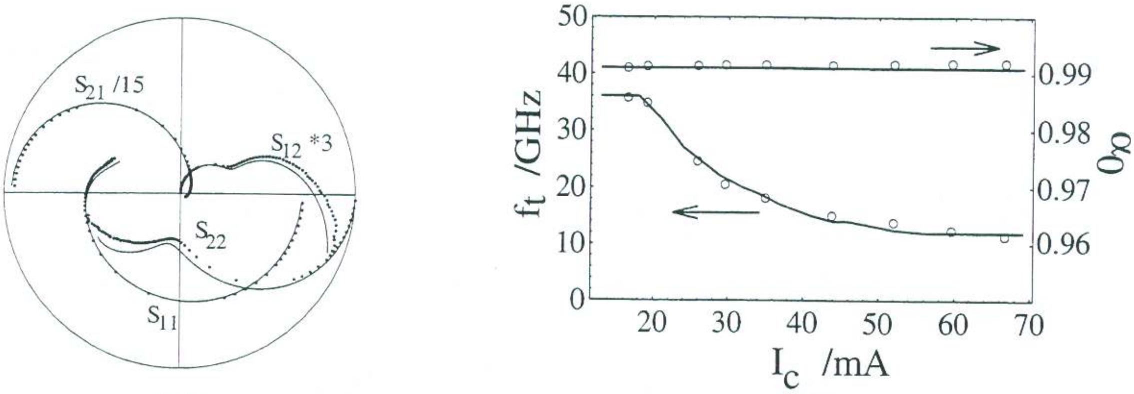


Figure 2.:Extrinsic network of the HBT.



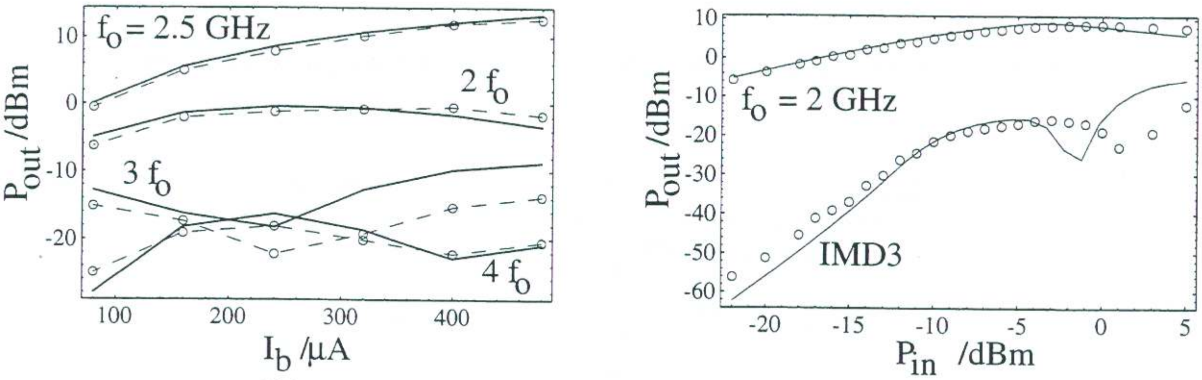
(A) **(B)**

Figure 3. **(A)**: GUMMEL plot (HBT A) (°: measurements, —: simulation). **(B)**: DC output characteristics with base current I_b as parameter (HBT A), $I_b = 0 - 2$ mA, Step = 200 μA (°: measurements, – –: conventional model, —: new model).



(A) **(B)**

Figure 4. (**A**): Measured and simulated S-parameters (HBT A) $f = 50$ MHz – 50 GHz, at $I_c = 23$ mA, $V_{ce} = 4$ V (°: measurements, —: simulation) (**B**): Measured and simulated variation of transit frequency and current gain with collector current (HBT B), $V_{ce} = 3$ V. (°: measurements, —: simulation).



(A) **(B)**

Figure 5. (**A**): Measured and simulated output power characteristics at one tone excitation (HBT A), $f_0 = 2.5$ GHz, $P_{in}=1$ dBm, $V_{ce} = 3$ V (°: measurements, —: simulation)
(**B**): Measured and simulated output power characteristics at two-tone excitation (HBT A), $f_0 = 2$ GHz, $\Delta f_0 = 100$ MHz, $I_c = 19$ mA, $V_{ce} = 3$ V. (°: measurements, —: simulation).